Quantifying Uncertainty in Early Lifecycle Cost Estimation for DOD Major Defense Acquisition Programs

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client offerings and provides measurement consulting to external clients.

Early cost estimation methods often result in highly inaccurate program cost predictions – and it continues to worsen

Table 1: Analysis of DOD Major Defense Acquisition Program Portfolios

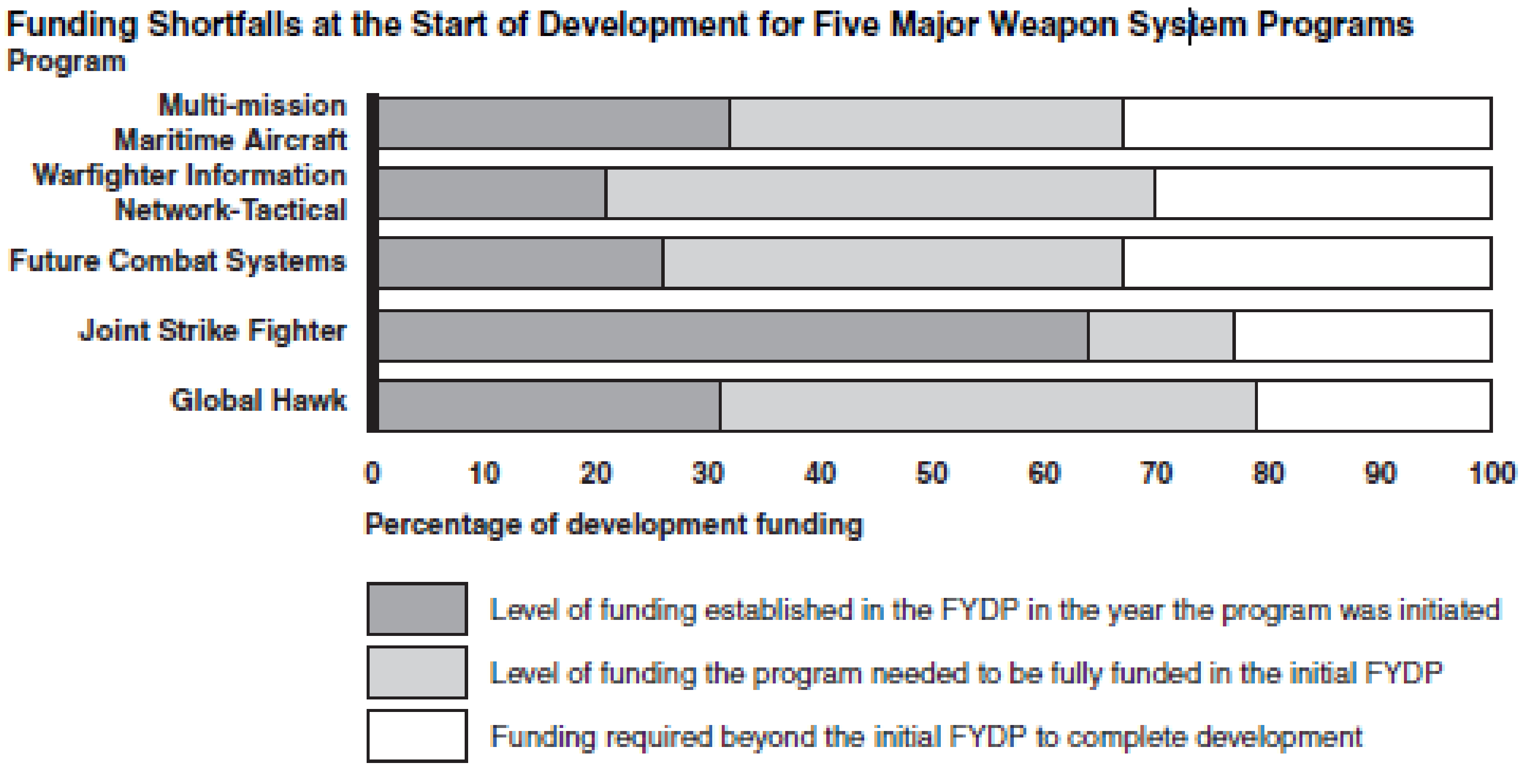
Fiscal year 2008 dollars			
	Fiscal year		
	2000 portfolio	**2005 portfolio**	**2007 portfolio**
Portfolio size			
Number of programs	75	91	95
Total planned commitments	$790 Billion	$1.5 Trillion	$1.6 Trillion
Commitments outstanding	$380 Billion	$887 Billion	$858 Billion
Portfolio performance			
Change to total RDT&E costs from first estimate	27 percent	33 percent	40 percent
Change in total acquisition cost from first estimate	6 percent	18 percent	26 percent
Estimated total acquisition cost growth	$42 Billion	$202 Billion	$295 Billion
Share of programs with 25 percent or more increase in program acquisition unit cost	37 percent	44 percent	44 percent
Average schedule delay in delivering initial capabilities	16 months	17 months	21 months

Source: GAO analysis of DOD data.

Unsustainable negative trend in cost predictions

Source: *Fundamental Changes Are Needed to Improve Weapon Program Outcomes*, GAO Testimony Before the Subcommittee on Federal Financial Management, Government Information, Federal Services, and International Security, Committee on Homeland Security and Governmental Affairs, U.S. Senate, Sept 25, 2008 GAO-08-1159T

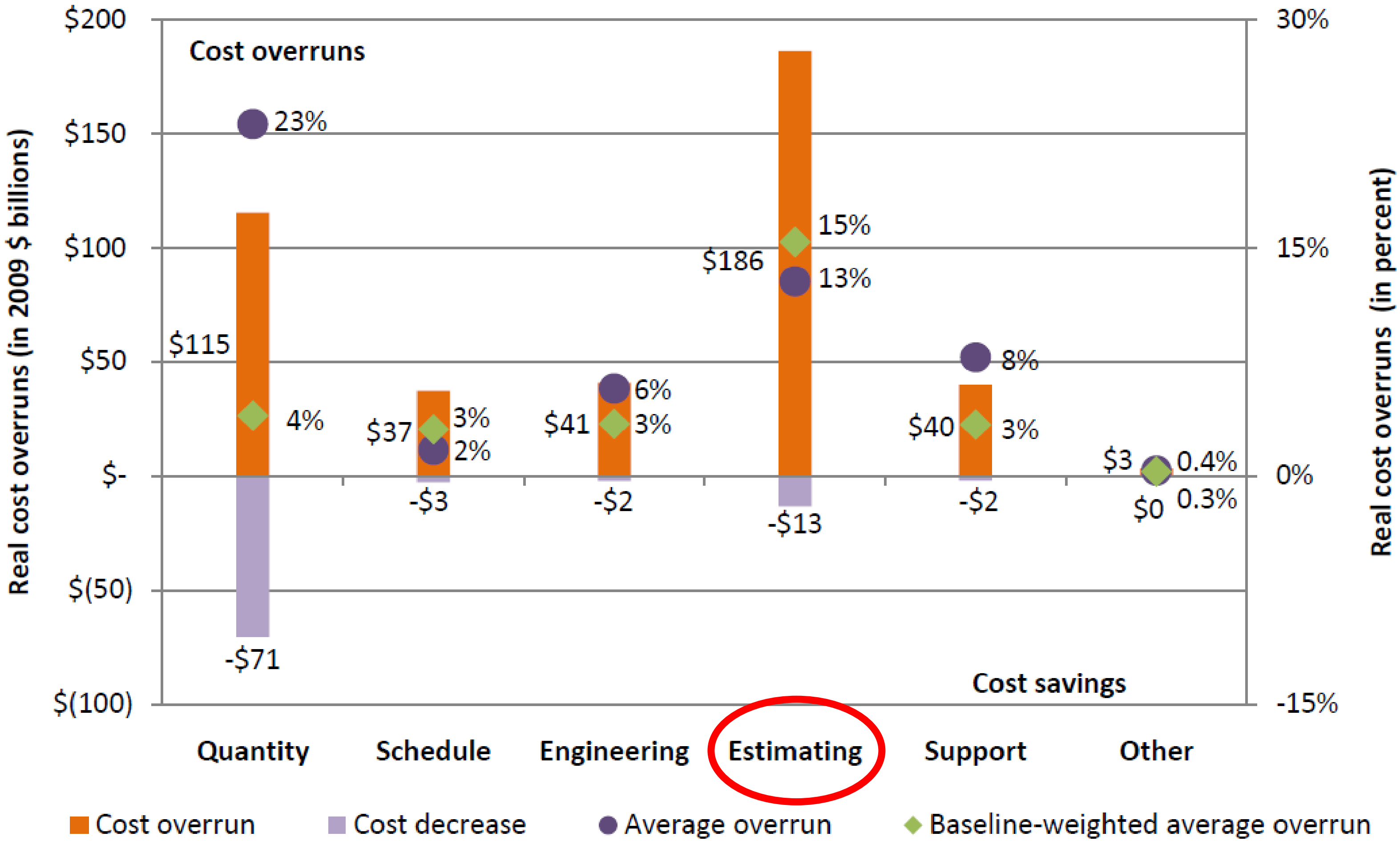
“DOD’s flawed funding process is largely driven by decision makers’ willingness to accept unrealistic cost estimates and DOD’s commitment to more programs than it can support. DOD often underestimates development costs—due in part to a lack of knowledge and optimistic assumptions about requirements and critical technologies.” *



Source: DOD (data); GAO (analysis and presentation).

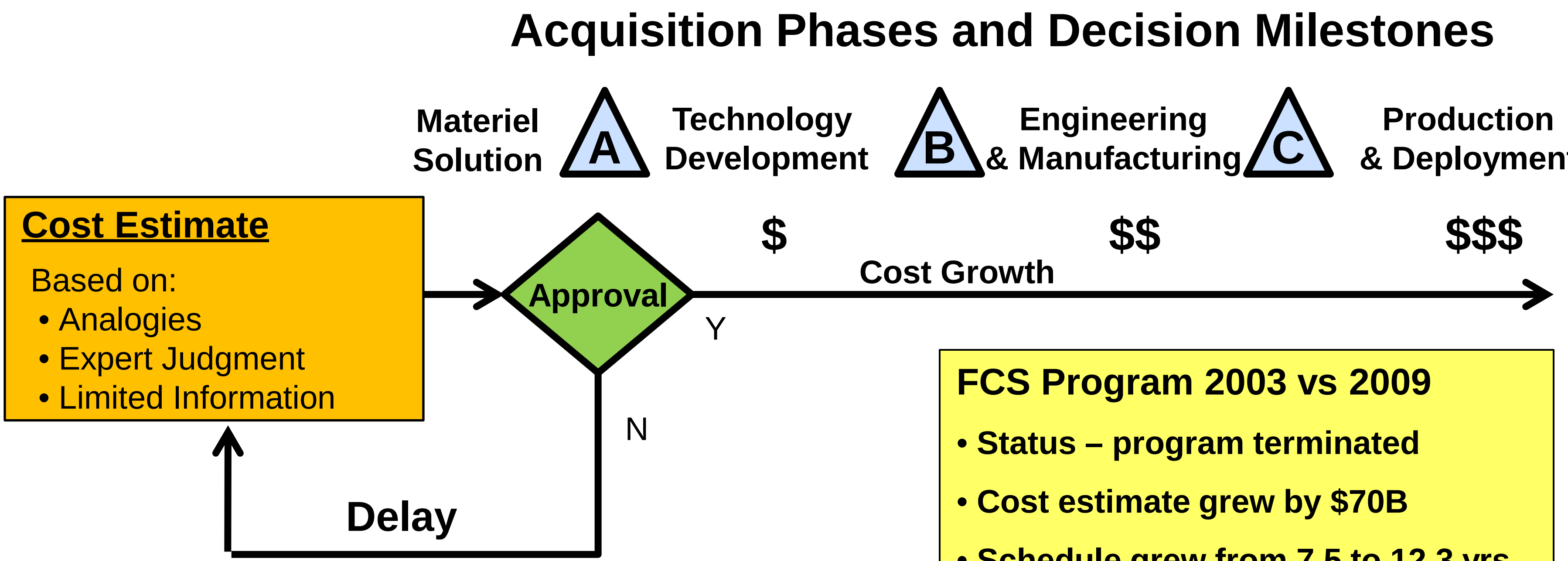
*Source: *A Knowledge-Based Funding Approach Could Improve Major Weapon System Program Outcomes*, GAO Report to the Committee on Armed Services, U.S. Senate s, U.S. Senate, July, 2008 GAO-08-619

Functional reasons for cost overruns



Source: December 2009 SAR; analysis by CSIS Defense-Industrial Initiatives Group
Cost and Time Overruns for Major Defense Acquisition Programs, 2010

DoD Acquisition Lifecycle



FCS Program 2003 vs 2009

- **Status – program terminated**
- **Cost estimate grew by $70B**
- **Schedule grew from 7.5 to 12.3 yrs**
- **Lines of code grew from 34M to 114M**

Source: GAO-10-406

Ground Combat Vehicle Delay Due to Reconciling Cost Estimates

- **4 months delay in obtaining approval to proceed**
- **Rework to conduct a new Analysis of Alternatives and to produce a new cost estimate**

Source: GAO-12-181T

Information Flow for Early Lifecycle Estimation

Expert Judgements

Information from Analogous Programs/Systems

Proposed Material Solution & Analysis of Alternatives

Program Execution Change Drivers

System Characteristics Trade-offs

- KPP selection
- Systems Design
- Sustainment issues

...

Operational Capability Trade-offs

- Mission / CONOPS
- Capability Based Analysis

...

Technology Development Strategy

- Production Quantity
- Acquisition Mgt
- Scope definition/responsibility
- Contract Award

Driver States & Probabilities

Plans, Specifications, Assessments

Probabilistic Modeling (BBN) & Monte Carlo Simulation

Cost Estimates

- analogy
- parametric
- engineering
- CERs

Program Execution Scenarios with conditional probabilities of drivers/states

Create a Method for Quantifying the Uncertainty of Cost Estimation Inputs and Resulting Estimates

Elements of Innovation

1. Identify Change Drivers & States	Explicit identification of domain specific program change drivers.
2. Reduce Cause and Effect Relationships via Dependency Structure Matrix techniques	Unique application of Dependency Structure Matrix techniques for cost estimation.
3. Assign Conditional Probabilities to BBN Model	BBN modeling of a larger number of program change drivers for estimation than previous research.
4. Calculate Cost Factor Distributions for Program Execution Scenarios	Scenario modeling of alternate program executions to assess influence of various underlying assumptions.
5. Monte Carlo Simulation to Compute Cost Distribution	Monte Carlo simulation applied to estimation input parameters rather than output values.

Technical Problem | **Complexity Reduction** | **Modeling Uncertainty**

Step 1: Identify Change Drivers and States

Materiel Solution Analysis Phase – Pre Milestone Estimate

A

1. Identify Change Drivers & States → 2. Reduce Cause and Effect Relationships via Dependency Structure Matrix techniques → 3. Assign Conditional Probabilities to BBN Model → 4. Calculate Cost Factor Distributions for Program Execution Scenarios → 5. Monte Carlo Simulation to Compute Cost Distribution

Change Driver	Nominal State	Alternative States				
Scope Definition	Stable	Users added	Additional (foreign) customer	Additional deliverable (e.g. training & manuals)	Production downsized	Scope Reduction (funding reduction)
Mission / CONOPS	As defined	New condition	New mission	New echelon	Program becomes Joint	
Capability Definition	Stable	Addition	Subtraction	Variance	Trade-offs [performance vs affordaility, etc.]	
Funding Schedule	Established	Funding delays tie up resources {e.g. operational test}	FFRDC ceiling issue	Funding change for end of year	Funding spread out	Obligated vs. allocated funds shifted
Advocacy Change	Stable	Joint service program loses particpant	Senator did not get re-elected	Change in senior pentagon staff	Advocate requires change in mission scope	Service owner different than CONOPS users
Closing Technical Gaps (CBA)	Selected Trade studies are sufficient	Technology does not achieve satisfactory performance	Technology is too expensive	Selected solution cannot achieve desired outcome	Technology not performing as expected	New technology not testing well
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Domain-Specific Program Change Drivers Identified

Step 2: Reduce Cause and Effect Relationships via Design Structure Matrix Techniques

Materiel Solution Analysis Phase – Pre Milestone Estimate

A

1. Identify Change Drivers & States → 2. Reduce complexity of Cause and Effect relationships via matrix techniques → 3. Assign Conditional Probabilities to BBN Model → 4. Calculate Cost Factor Distributions for Program Execution Scenarios → 5. Monte Carlo Simulation to Compute Cost Distribution

Change Drivers - Cause & Effects Matrix

Causes \ Effects	Mission / CONOPS	Change in Strategic Vision	Capability Definition	Advocacy Change	Closing Technical Gaps (CBA)	Building Technical Capability & Capacity (CBA)	Interoperability	Systems Design	Interdependency	Functional Measures	Scope Definition	Functional Solution Criteria (measure)	Funding Schedule	Acquisition Management	Program Mgt - Contractor Relations	Project Social / Dev Env	Prog Mgt Structure	Manning at program office
Mission / CONOPS			3								3							
Change in Strategic Vision			3	3		3			2				2					
Capability Definition								3					0	2	1	1	0	0
Advocacy Change											2			1			1	1
Closing Techn																		
Building Tech																		
Interoperabili																		
Systems Des																		

Capturing interrelationships among change drivers and reducing the complexity of the network

Step 2: Reduce Cause and Effect Relationships via Dependency Structure Matrix Techniques

Change Drivers - Cause & Effects Matrix

Causes \ Effects	Mission / CONOPS	Change in Strategic Vision	Capability Definition	Advocacy Change	Closing Technical Gaps (CBA)	Building Technical Capability & Capacity (CBA)	Interoperability	Systems Design	Interdependency	Functional Measures	Scope Definition	Functional Solution Criteria (measure)	Funding Schedule	Acquisition Management	Program Mgt - Contractor Relations	Project Social / Dev Env	Prog Mgt Structure	Manning at program office	Scope Responsibility	Standards/Certifications	Supply Chain Vulnerabilities	Information sharing	PO Process Performance	Sustainment Issues	Contract Award	Production Quantity	Data Ownership	Industry Company Assessment	Cost Estimate	Test & Evaluation	Contractor Performance	Size	Project Challenge	Product Challenge	Total	Number right of diagonal
Mission / CONOPS			3								3								0																6	0
Change in Strategic Vision			3	3		3			2				2									2		2	2	3		2	3	2					29	0
Capability Definition								3					0	2	1	1	0	0		2	2	2	0	1	0	2	0				0				16	0
Advocacy Change											2			1			1	1	1																6	0
Closing Technical Gaps (CBA)						2	1	3	1	2		2		1	2	2			1	1	2	1	0	2	2	1	1	2	2	1	2				34	0
Building Technical Capability & Capacity (CBA)									1	1		2		1	2	2	1				2	3		2	2	1	2	2	1	1	1				27	0
Interoperability						1		2	1		1	1		1	1	1			1	1	2	1	1	2			1		1	3	1	2	2	2	29	1
Systems Design						1	2		2	2		2							1		1	1		1			1	2	2	3					21	3
Interdependency				1			2	2			1	1	1		1	1	1	1	1	1	2	1	2	2			1	1	1	1	1	2	2	3	33	5
Functional Measures												2			2	2				1	1	1	1		1		1	1		2	1				16	0
Scope Definition																	1	1	3																5	0
Functional Solution Criteria (measure)									1						2	2				1								1		2	1				10	1
Funding Schedule														1				1					2								1				5	0
Acquisition Management										1		1			2	3					1	1	2		2		1	1	1		2			1	19	2
Program Mgt - Contractor Relations										1		1				2						1	1	1						1	2			2	12	2
Project Social / Dev Env														1	1							1	2		2		1			1	2	1	1	1	14	2
Prog Mgt Structure																1		2				1	2												6	1
Manning at program office																	2					1	2												5	2
Scope Responsibility														1	1	1	1	1					1												6	5
Standards/Certifications						1						1									1			1	1			1		3	1				10	2
Supply Chain Vulnerabilities								1					1	1						1						2					1				7	4
Information sharing					1	1		1															1	1			1				1				7	3
PO Process Performance																															2			2	4	0
Sustainment Issues																																			0	0
Contract Award																																			0	0
Production Quantity																																		2	2	0
Data Ownership																																		2	2	0
Industry Company Assessment																																			0	0
Cost Estimate																																			0	0
Test & Evaluation																																			0	0
Contractor Performance																																		2	2	0
Size																																			0	0
Project Challenge																																			0	0
Product Challenge																																			0	0
Totals	0	0	6	4	1	9	5	12	8	7	7	13	4	10	15	18	7	7	8	8	14	17	17	15	12	9	10	13	11	20	19	5	5	17		
Below diagonal	0	0	0	1	1	4	4	4	1	2	0	3	1	3	2	2	3	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0		

Step 3: Assign Conditional Probabilities to BBN Model

Materiel Solution Analysis Phase – Pre Milestone Estimate A

1. Identify Change Drivers & States →
2. Reduce Cause and Effect Relationships via Dependency Structure Matrix techniques →
3. Assign Conditional Probabilities to BBN Model →
4. Calculate Cost Factor Distributions for Program Execution Scenarios →
5. Monte Carlo Simulation to Compute Cost Distribution

Capability Definition

Node Probability Table

NPT Editing Mode .... Manual

Mission CONOPS	0.0		1.0	
Strategic Vision	0.0	1.0	0.0	1.0
0.0	0.4	0.3	0.25	0.2
1.0	0.6	0.7	0.75	0.8

Node States

Quantifying the uncertainty of change drivers and the cascading effects

Capability Definition is affected by CONOPS and Strategic Vision

Step 4: Calculate Cost Factor Distributions for Program Execution Scenarios

Materiel Solution Analysis Phase – Pre Milestone Estimate A

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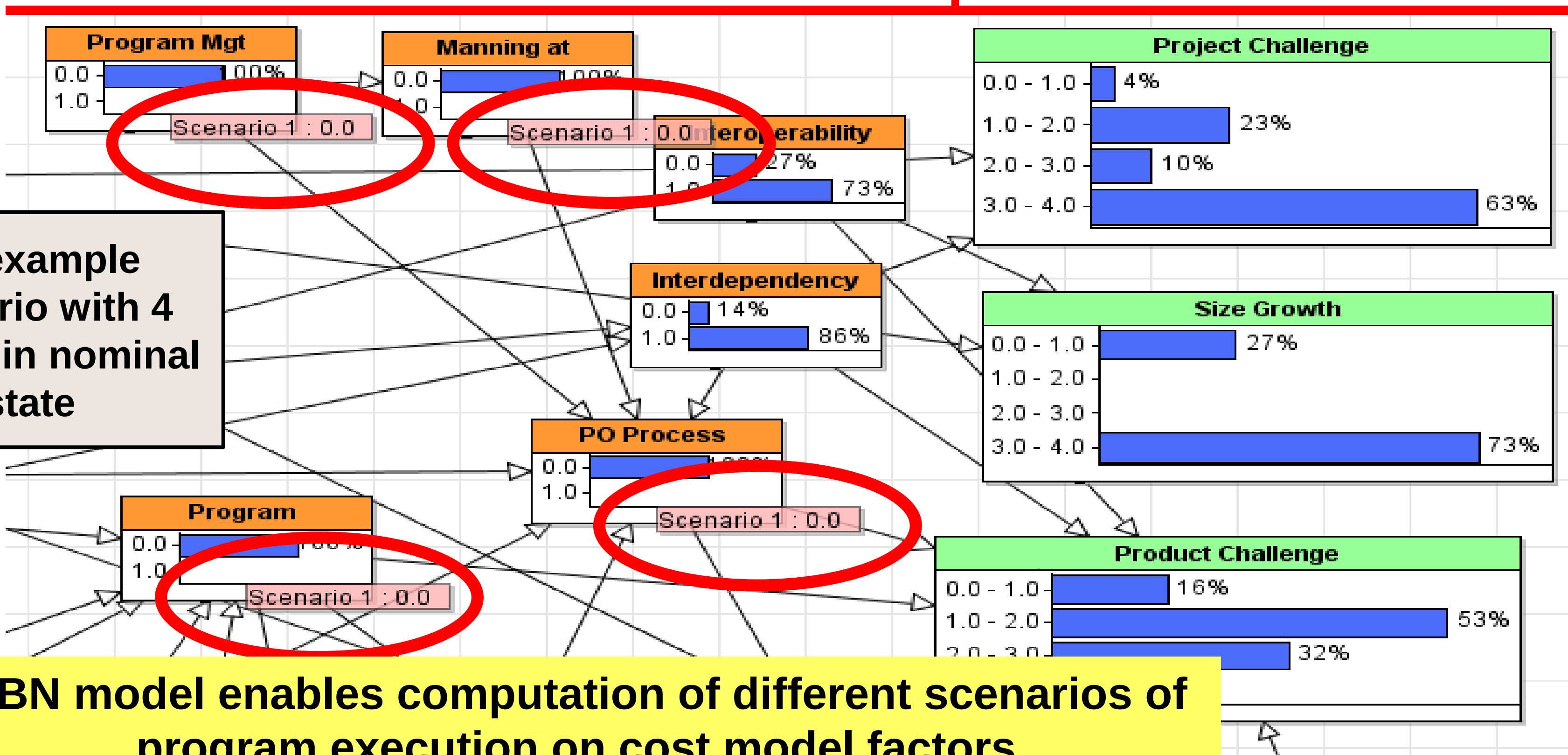

An example scenario with 4 drivers in nominal state

BBN model enables computation of different scenarios of program execution on cost model factors

Step 5a: Monte Carlo Simulation to Compute Cost Distribution

Materiel Solution Analysis Phase – Pre Milestone Estimate A

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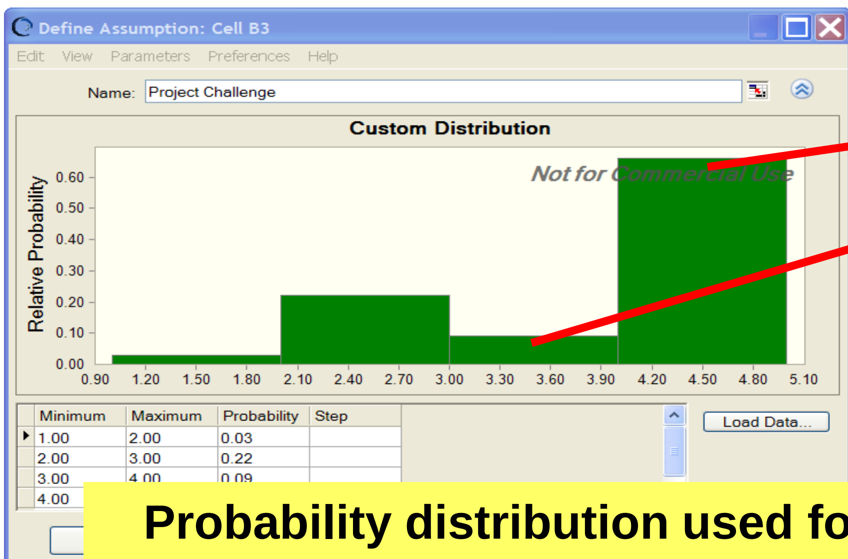
BBN output distributions mapped to COCOMO input values



Drivers	XL	VL	L	N	H	VH	XH	Product	Project
Scale Factors									
PREC		6.20	4.96	3.72	2.48	1.24	0.00		<X>
FLEX		5.07	4.05	3.04	2.03	1.01	0.00	<X>	
RESL		7.07	5.65	4.24	2.83	1.41	0.00	<X>	
TEAM		5.48	4.38	3.29	2.19	1.10	0.00		<X>
PMAT		7.80	6.24	4.68	3.12	1.56	0.00		<X>
Effort Multipliers									
RCPX	0.49	0.60	0.83	1.00	1.33	1.91	2.72	X	
RUSE			0.95	1.00	1.07	1.15	1.24	X	
PDIF			0.87	1.00	1.29	1.81	2.61	X	
PERS	2.12	1.62	1.26	1.00	0.83	0.63	0.50	<X>	
PREX	1.59	1.33	1.12	1.00	0.87	0.74	0.62		<X>
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Probability distribution used for input to cost estimation model links uncertainty of program change drivers to cost drivers

COCOMO “Architecture” Parameter Mapping

Product challenge factors represent uncertainty in performance criteria and technology.

- PREC: Is this application unprecedented?
- FLEX: How stringent are the product goals, scope and objectives?
- RCPX: What is required product reliability and complexity?
- RUSE: Must we design for re-usability?
- PDIF: Platform difficulty? Processing speed, memory? Platform stability?
- RESL: Have we addressed technology & architecture risk?

Project challenge factors represent difficulty in managing the workforce.

- PREX: Personnel capability and experience?
- SCED: How much schedule pressure is applied to this development?
- FCIL: Are facilities adequate? Includes tools and multi-site development.
- TEAM: Do we have a cohesive development team?
- PMAT: Does the organization have a mature process?

Step 5b: Monte Carlo Simulation to Compute Cost Distribution

Materiel Solution Analysis Phase – Pre Milestone Estimate A

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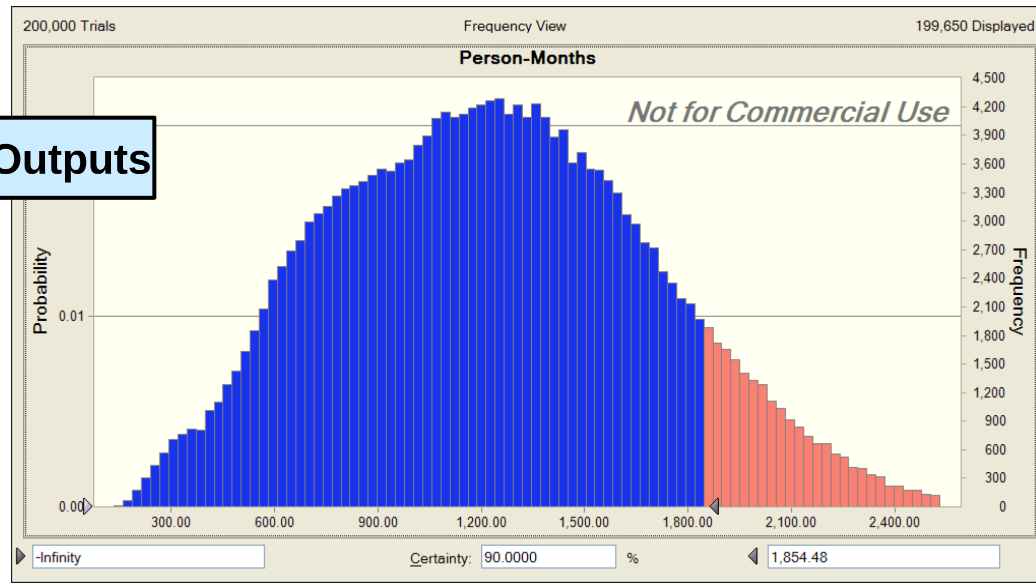
Monte Carlo simulation using program change factor distributions uses uncertainty on the input side to determine the cost estimate distribution

	A	B	C	D
1	Effect			
2	Product Challenge	5		
3	Project Challenge	4		
4	Estimated Size (KSLOC)	50		
5	Product Challenge factors		5	
6	COCOMO Parameter		XL	VL
7	Scale Factors	PREC		4
8		Val		6.2
9		FLEX		5

BBN Outputs

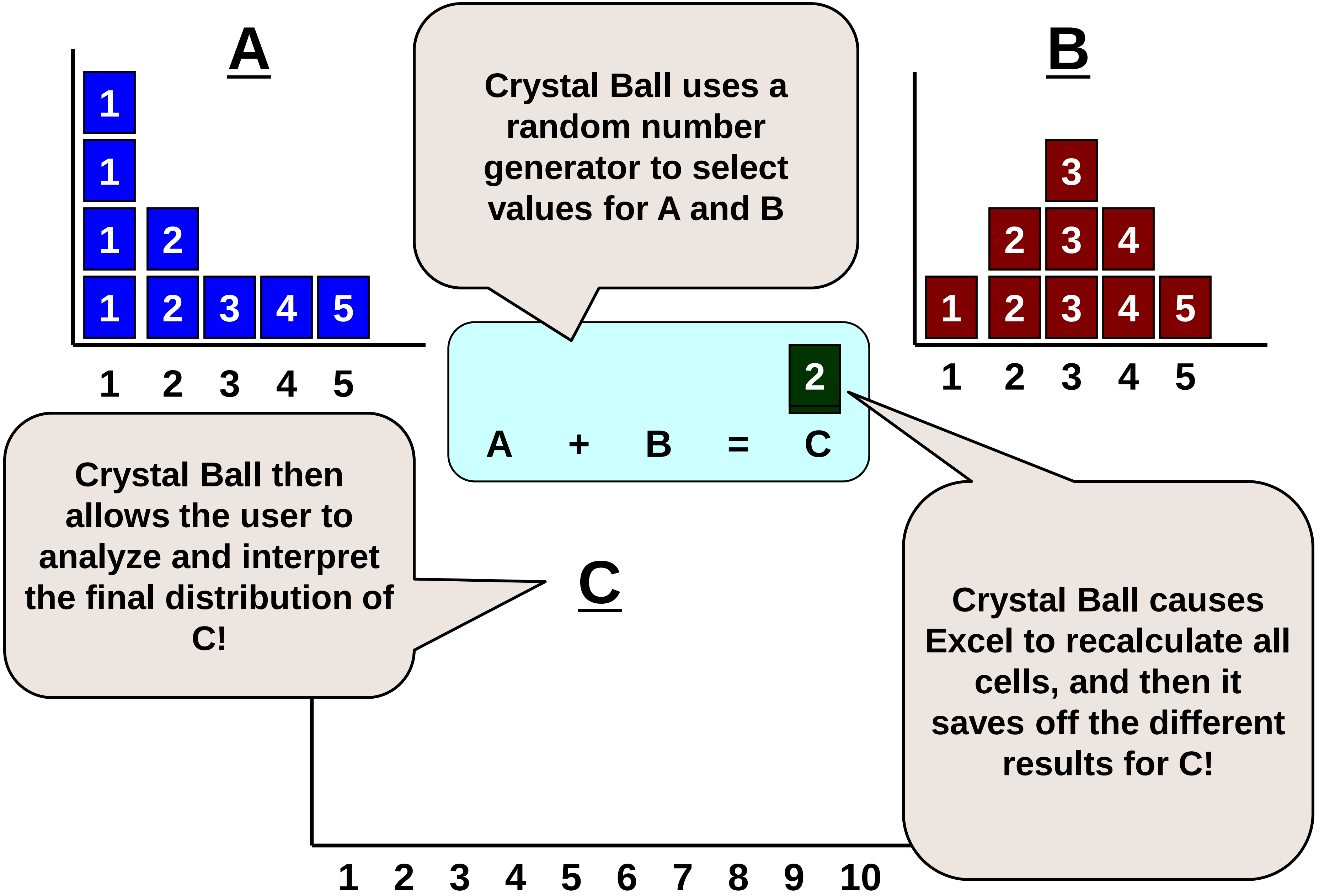
Mapped COCOMO value



Monte Carlo Simulation

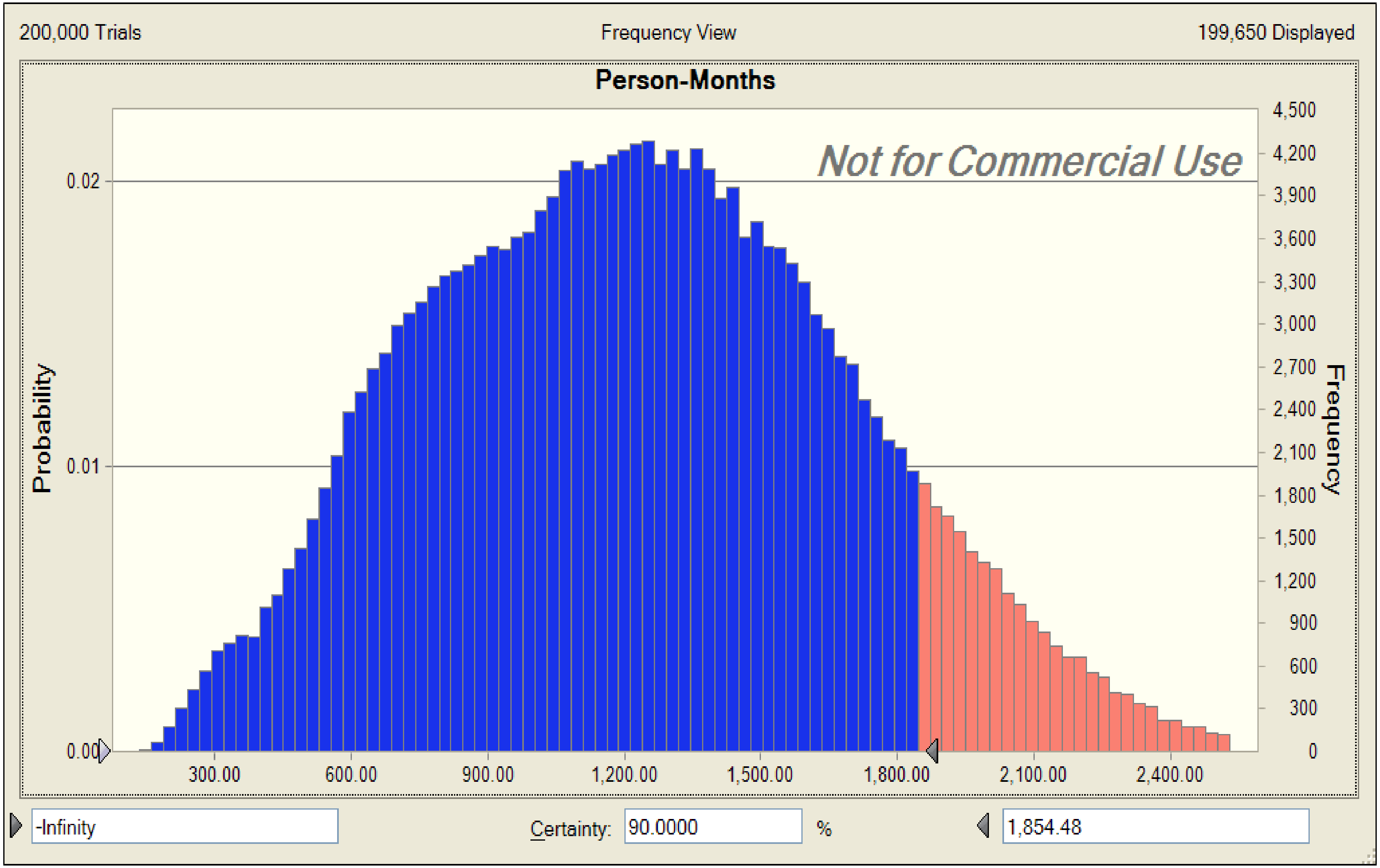
We will use Monte Carlo simulation to connect the BBN output node distributions to the COCOMO input parameter distributions

The animation on the next slide depicts the essence of Monte Carlo simulation when we need to work with distributions rather than single numbers



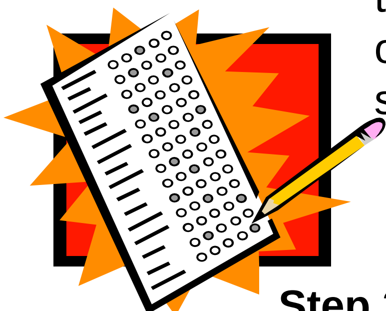
A
1
1
1 2
1 2 3 4 5
1 2 3 4 5
Crystal Ball uses a random number generator to select values for A and B
B
3
2 3 4
1 2 3 4 5
1 2 3 4 5
2
A + B = C
Crystal Ball then allows the user to analyze and interpret the final distribution of C!
C
Crystal Ball causes Excel to recalculate all cells, and then it saves off the different results for C!
1 2 3 4 5 6 7 8 9 10

An Example Output of Monte Carlo Simulation

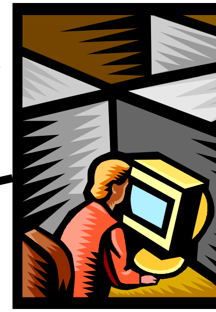


Develop Efficient Techniques To Calibrate Expert Judgment of Program Uncertainties

Solution



Step 2: Iterate through a series of domain specific tests

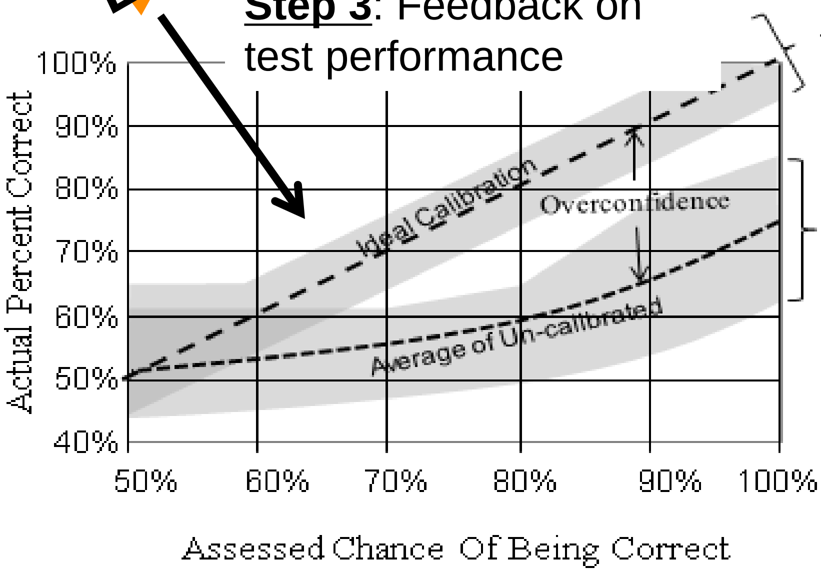


Step 1: Virtual training using reference points

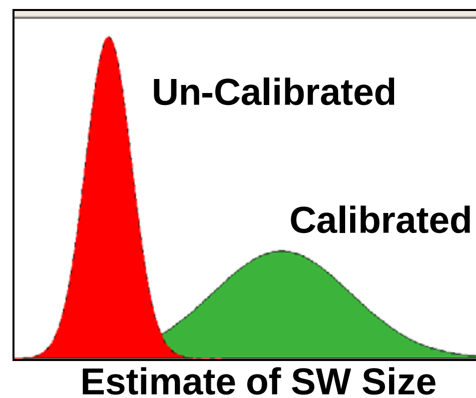
DoD Domain-Specific reference points

1) **Size of ground combat vehicle targeting feature xyz in 2002 consisted of 25 KSLOC Ada**
2) **Size of Army artillery firing capability feature abc in 2007 consisted of 18 KSLOC C++**
3) **…**

Step 3: Feedback on test performance



Outcome: Expert renders calibrated estimate of size



Calibrated = more realistic size and wider range to reflect true expert uncertainty

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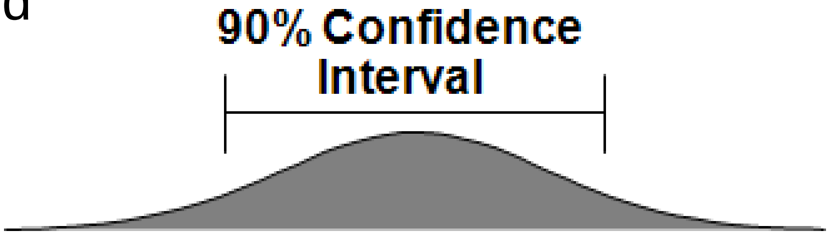
Polling Question 1

Do you find that your current cost estimation process relies heavily on expert judgment?

1. Yes
2. No
3. Not Sure

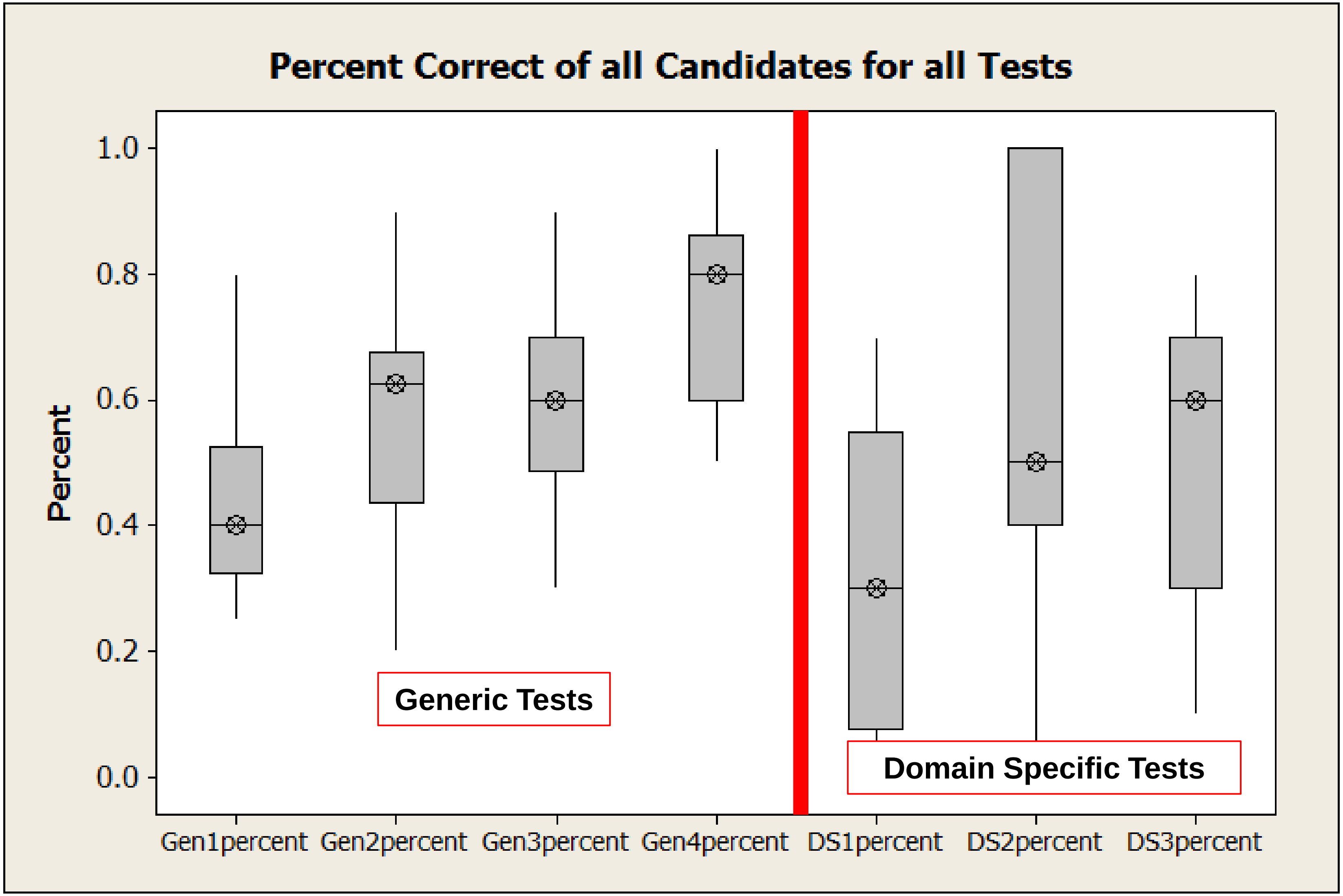
Experts Tend to Be Over-Confident

Most people are significantly ***overconfident*** about their estimates, especially educated professionals



(AIE = Hubbard Generic Calibration Training)

Group	Subject	% Correct (target 90%)
Harvard MBAs	General Trivia	40%
Chemical Co. Employees	General Industry	50%
Chemical Co. Employees	Company-Specific	48%
Computer Co. Managers	General Business	17%
Computer Co. Managers	Company-Specific	36%



Experiments confirm that calibrated judgment can be taught.

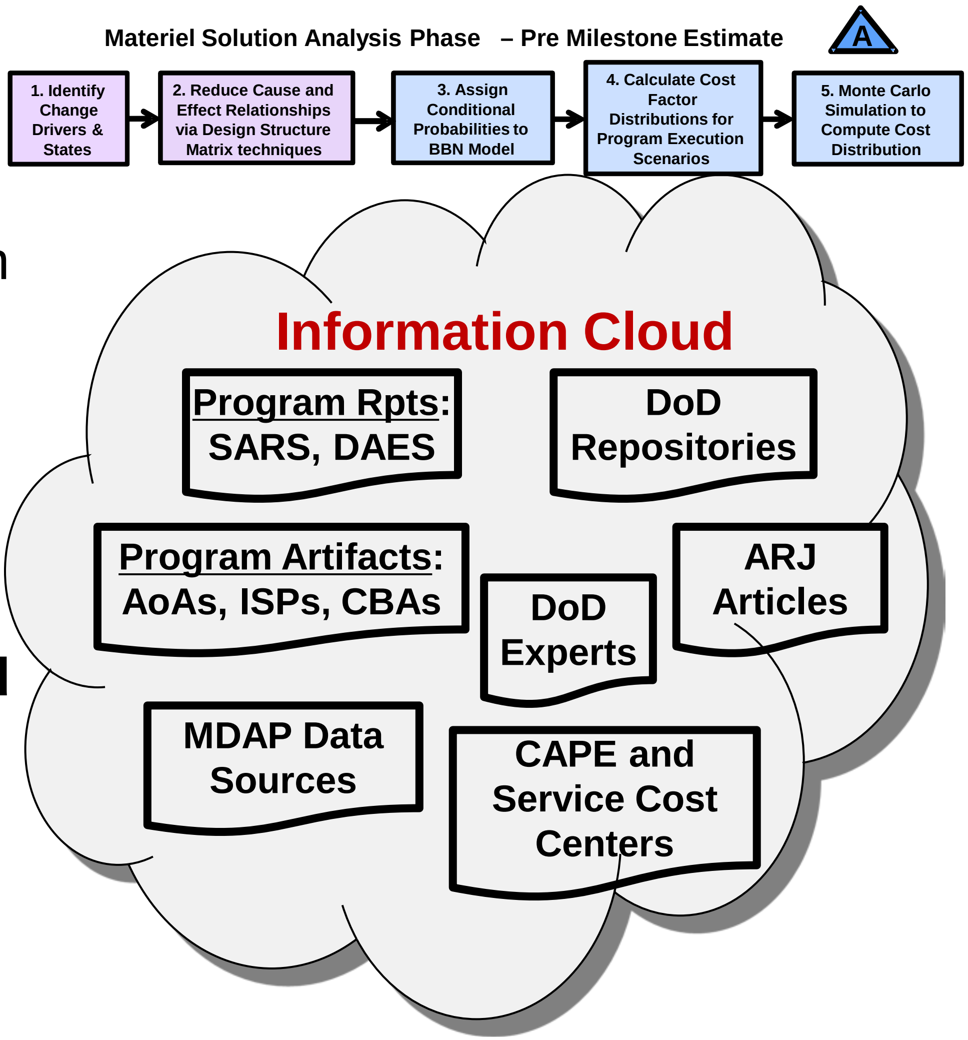
Future Research Activities

Create A Repository for Quantifying Program Execution Uncertainties

Subject Matter Experts need DoD MDAP **data about uncertainty** to quantify relationships of program change drivers and their impact on program execution.

Why Hard? Empirical data need to be identified, accessed, extracted and analyzed from a **myriad of sources**. Data about program change is **not structured nor quantified** for use in estimation.

DoD Need: Quantified information about **cost driver uncertainty** should inform estimates.



Repository: Analyze Existing Data to Model Program Execution Uncertainties - 1

Solution

Materiel Solution Analysis Phase – Pre Milestone Estimate

A

1. Identify Change Drivers & States → 2. Reduce Cause and Effect Relationships via Dependency Structure Matrix techniques → 3. Assign Conditional Probabilities to BBN Model → 4. Calculate Cost Factor Distributions for Program Execution Scenarios → 5. Monte Carlo Simulation to Compute Cost Distribution

Program Change Repository

Prog	State	Driver
DDG51	cond 1	CONOPS
	cond 2	System
	cond 3	CapDef
JTRS	cond 1	InterOp
	cond 2	Prod uc
F22	cond 1	Contract
	cond 2	Function
	cond 3	CONOPS

For C2 systems, how often does Strategic Vision change?

Records show that Strategic Vision changed in 45% of the MDAPS

Driver State Matrix

Change Driver	Nominal State	Alternative States				
Scope Definition	Stable	Users added	Additional (foreign) customer	Additional deliverable (e.g. training & manuals)	Production downsized	Scope Reduction (funding reduction)
Mission / CONOPS	defined	New condition	New mission	New echelon	Program becomes Joint	
Capability Definition	Stable	Addition	Subtraction	Variance	Trade-offs [performance vs affordaility, etc.]	
Funding Schedule	Established	Funding delays tie up resources {e.g. operational test}	FFRDC ceiling issue	Funding change for end of year	Funding spread out	Obligated vs. allocated funds shifted
Advocacy Change	Stable	Joint service program loses particpant	Senator did not get re-elected	Change in senior pentagon staff	Advocate requires change in mission scope	Service owner different than CONOPS users
Closing Technical Gaps (CBA)	Selected Trade studies are sufficient	Technology does not achieve satisfactory performance	Technology is too expensive	Selected solution cannot achieve desired outcome	Technology not performing as expected	New technology not testing well
•	~~~~	~~~~	~~~~			
•	~~~~	~~~~	~~~~	~~~~		
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The **Materiel Solution** of a global network command and control system anticipates a possible change in **Strategic Vision** which will include allied participation.

Sharing information with allies creates new encryption requirements (a change in **Mission/CONOPs).**

These changes lead to changes in **Capability**

Repository identifies probability of change in MDAP cost drivers.

Repository: Analyze Existing Data to Model Program Execution Uncertainties - 2

Solution

Materiel Solution Analysis Phase – Pre Milestone Estimate A

1. Identify Change Drivers & States → 2. Reduce Cause and Effect Relationships via Dependency Structure Matrix techniques → 3. Assign Conditional Probabilities to BBN Model → 4. Calculate Cost Factor Distributions for Program Execution Scenarios → 5. Monte Carlo Simulation to Compute Cost Distribution

Program Change Repository

Prog	State	Driver
DDG51	cond 1	CONOPS
	cond 2	System De
	cond 3	CapDef
JTRS	cond 1	InterOpera
	cond 2	Prod uctio
F22	cond 1	Contract
	cond 2	Functional
	cond 3	CONOPS

If Strategic Vision changes, what else changes?

70% of the time the Mission/CONOPS changes

The **Materiel Solution** of a global network command and control system anticipates a possible change in **Strategic Vision** which will include allied participation.

Sharing information with allies creates new encryption requirements (a change in **Mission/CONOPs).**

Driver State Matrix

Change Driver	Nominal State	Alternative States				
Scope Definition	Stable	Users added	Additional (foreign) customer	Additional deliverable (e.g. training & manuals)	Production downsized	Scope Reduction (funding reduction)
Mission / CONOPS	defined	New condition	New mission	New echelon	Program becomes Joint	
Capability Definition	Stable	Addition	Subtraction	Variance	Trade-offs [performance vs affordaility, etc.]	
Funding Schedule	Established	Funding delays tie up resources {e.g. operational test}	FFRDC ceiling issue	Funding change for end of year	Funding spread out	Obligated vs. allocated funds shifted
Advocacy Change	Stable	Joint service program loses particpant	Senator did not get re-elected	Change in senior pentagon staff	Advocate requires change in mission scope	Service owner different than CONOPS users
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•	~~~~	~~~~	~~~~			
•	~~~~	~~~~	~~~~	~~~~		
•	~~~~	~~~~	~~~~	~~~~	~~~~	~~~~

DSM Cause-Effect Matrix

Change Drivers - Caus

Causes \ Effects	Mission / CONOPS	Change in Strategic Vision	Capability Definition	Advocacy Change	Closing Technical Gaps (CBA)	Building Technical Capability & Capacity (CBA)	Interoperability
Mission / CONOPS			3				
Change in Strategic Vision			3	3		3	
Capability Definition							
Advocacy Change							
Closing Technical Gaps (CBA)						2	1
Building Technical Capability & Capacity (CBA)							
Interoperability						1	
Systems Design						1	2
Interdependency				1			2

Repository identifies cascading effects of change in MDAP cost drivers.

Repository: Analyze Existing Data to Model Program Execution Uncertainties - 3

Solution

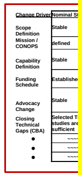
Materiel Solution Analysis Phase – Pre Milestone Estimate A

1. Identify Change Drivers & States → **2. Reduce Cause and Effect Relationships via Dependency Structure Matrix techniques** → **3. Assign Conditional Probabilities to BBN Model** → **4. Calculate Cost Factor Distributions for Program Execution Scenarios** → **5. Monte Carlo Simulation to Compute Cost Distribution**

$$P(A_i \mid A) = \frac{P(A_i)\,P(A \mid A_i)}{\sum_i P(A_i)\,P(A \mid A_i)}$$

When both Strategic Vision & Mission/CONOPs experience change, the BBN calculates that Capability Definition will also change 95% of the time.

Dr



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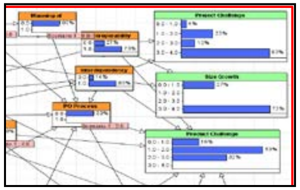
BBN Model



Joint Conditional Probabilities can be calculated for downstream changes.

The <u>**Materiel Solution**</u> of a global network command and control system anticipates a possible change in **Strategic Vision** which will include allied participation.

Sharing information with allies creates new encryption requirements (a change in **Mission/CONOPs).**

These changes lead to changes in **Capability Definition**.

QUELCE Summary

QUELCE includes the effects of uncertainty in the resulting estimate by:

- Making visible the quantified uncertainties that exist in basic assumptions.
- Calculating uncertainty of the input factors to the model rather than adjusting the output factors.
- Using scenario planning to calculate how specific changes might affect outcomes.

The method utilizes subjective and objective data as input

- Historical data can be used to populate the BBN nodes and establish the connections between the BBN and cost model inputs.
- Expert judgments are documented and made explicit.
- Information typically not used for estimation purposes can be leveraged.

The method explicitly includes factors that have been documented as sources of program failure in the past but are not typically captured by cost models

For More Information

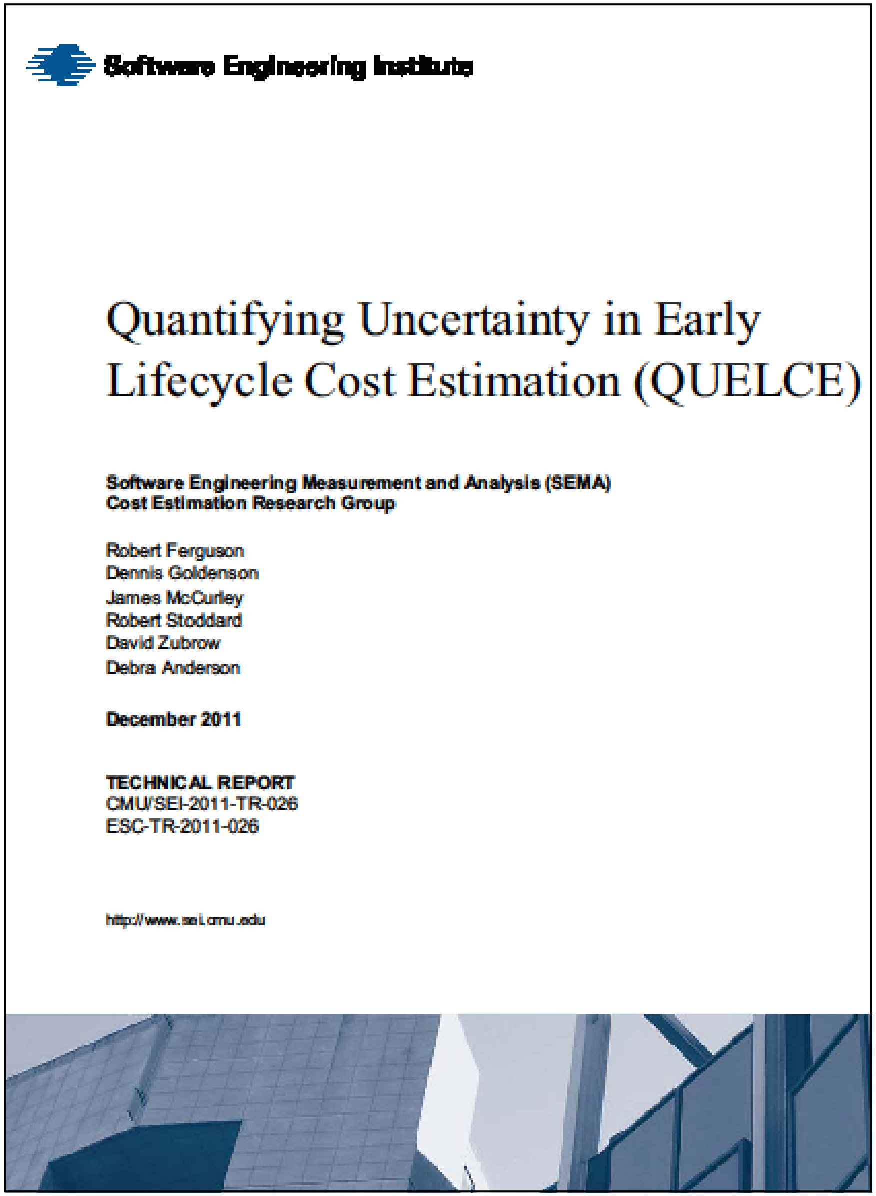
QUELCE Technical Report:
http://www.sei.cmu.edu/library/abstracts/reports/11tr026.cfm

SEI Blog
http://blog.sei.cmu.edu

- "Improving the Accuracy of Early Cost Estimates for Software-Reliant Systems, First in a Two-Part Series"
- "A New Approach for Developing Cost Estimates in Software Reliant Systems, Second in a Two-Part Series"
- "Quantifying Uncertainty in Early Lifecycle Cost Estimation (QUELCE): An Update"

Journal of Software Technology
http://journal.thedacs.com/issue/64/207

- "An Innovative Approach to Quantifying Uncertainty in Early Lifecycle Cost Estimation"


Software Engineering Institute

Quantifying Uncertainty in Early Lifecycle Cost Estimation (QUELCE)

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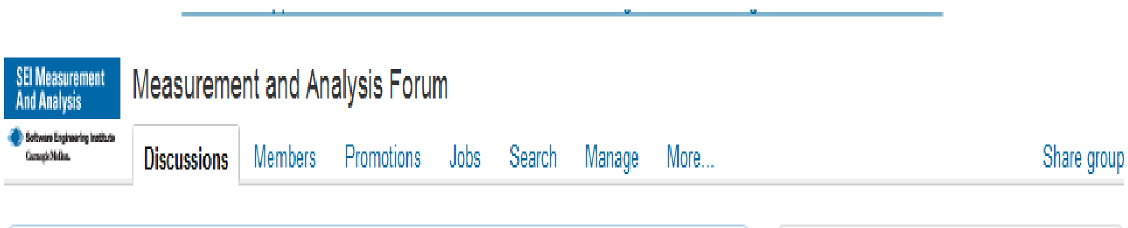

http://www.linkedin.com/groups/Measurement-Analysis-Forum-2758144